



Advanced Micro Ring Resonator Filter Technology

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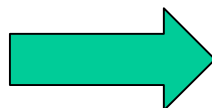
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All-Pass Filters

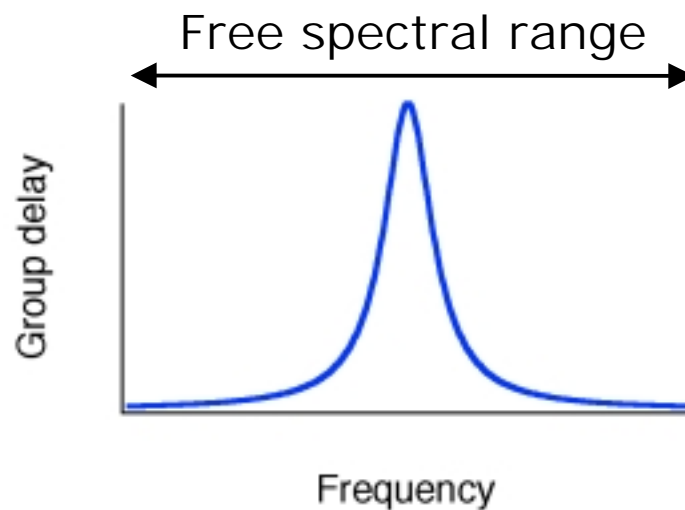
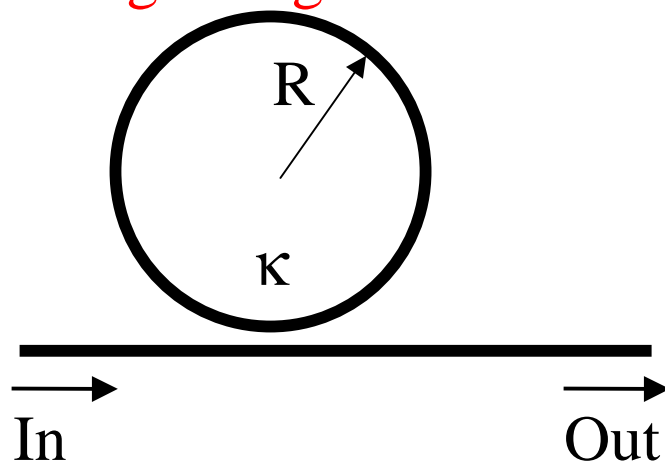
$$|H(\omega)| = 1$$

$$\phi(\omega) = \text{arbitrary}$$



- ◆ Phase equalization
- ◆ Dispersion compensation
- ◆ Optical delay line

Single stage APF



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Mathematical Form

$$H(\omega) = \prod_{n=0}^{N-1} \frac{e^{j\omega} - z_n}{e^{j\omega} z_n^* - 1} = \prod_{n=0}^{N-1} \frac{e^{j\omega} - r_n e^{j\theta_n}}{e^{j\omega} r_n e^{-j\theta_n} - 1}$$

$$|H(\omega)| = 1$$

$$\phi(\omega) = \sum_{n=0}^{N-1} \text{Arg} \left[\frac{e^{j\omega} - z_n}{e^{j\omega} z_n^* - 1} \right]$$



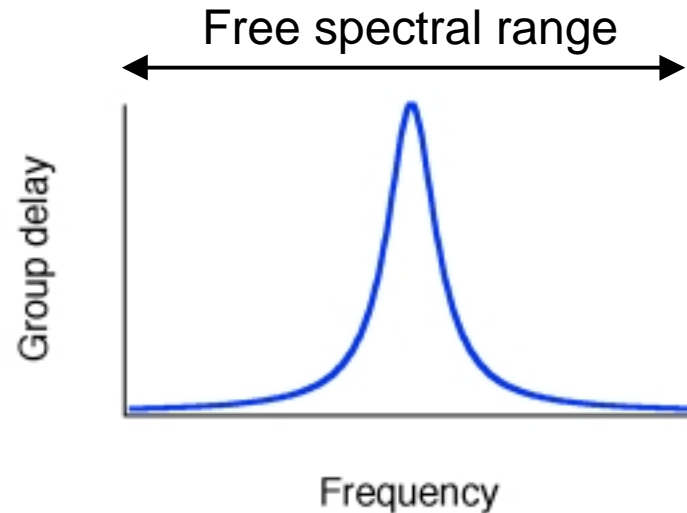
Phase equalization without
amplitude distortion



Group Delay

$$\tau(\omega) = \sum_{n=0}^{N-1} \frac{\sinh \chi_n}{\cosh \chi_n - \cos(\omega - \theta_n)}$$

$$\chi_n = \ln r_n$$



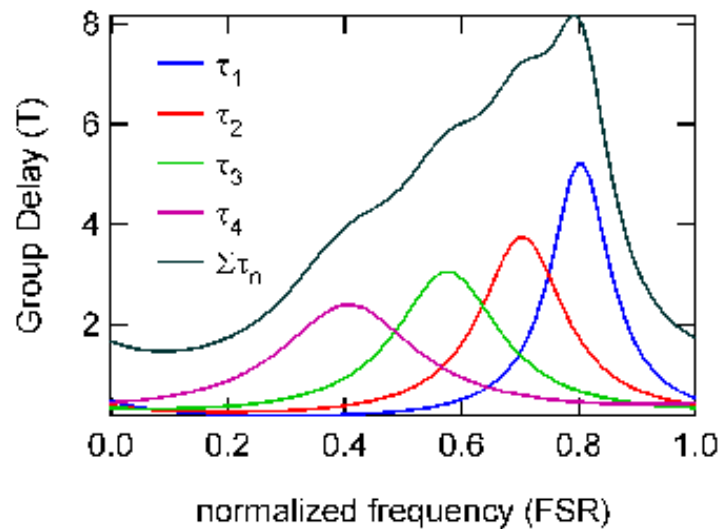
$$D(\omega) = \frac{d\tau(\omega)}{d\omega} \propto \frac{1}{FSR^2}$$

Larger FSR \Rightarrow smaller dispersion; More stages \Rightarrow more dispersion

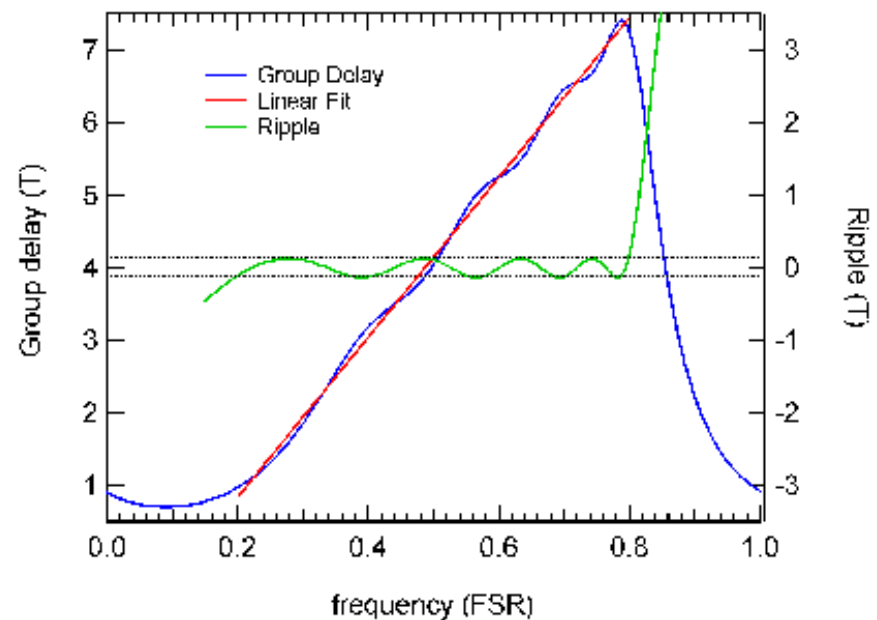


Four-Stage All-Pass Filter

*Approximation of
Linear group delay
across pass band*



Equi-ripple design

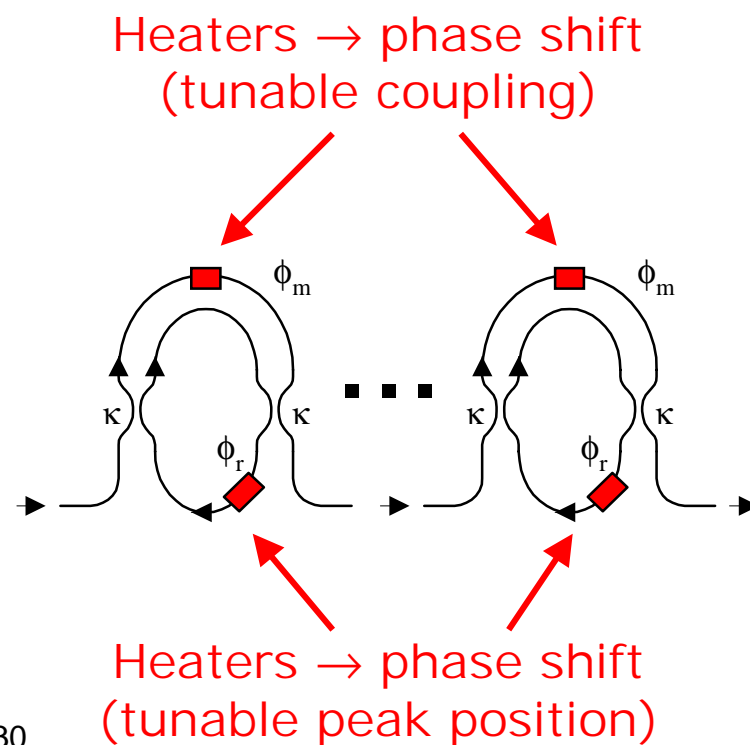
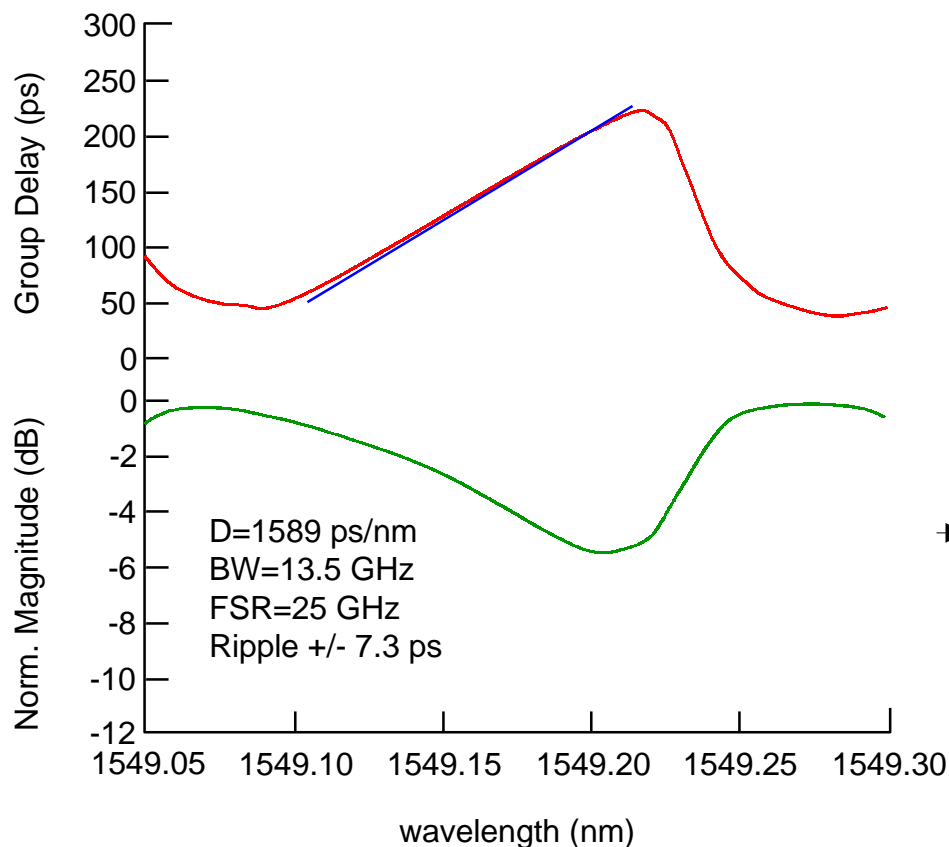


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Four-Stage All-Pass Filter Experimental

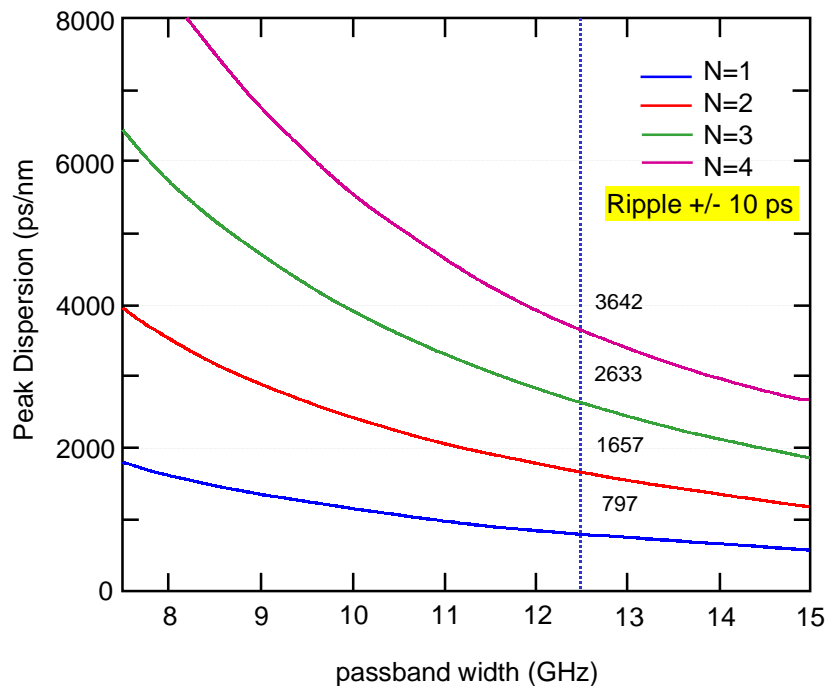


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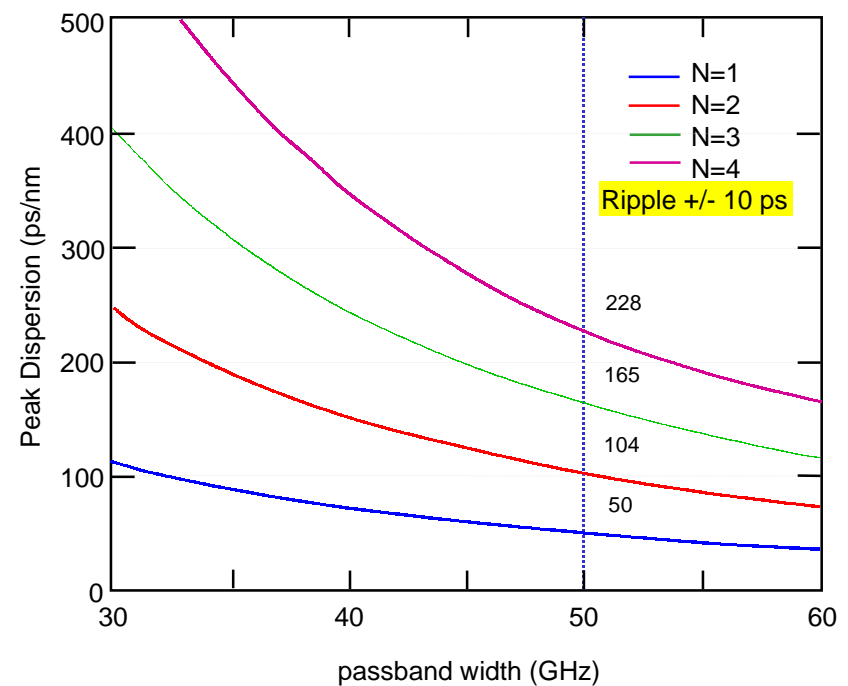
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Dispersion vs. Bandwidth Tradeoff

25 GHz Channel Spacing



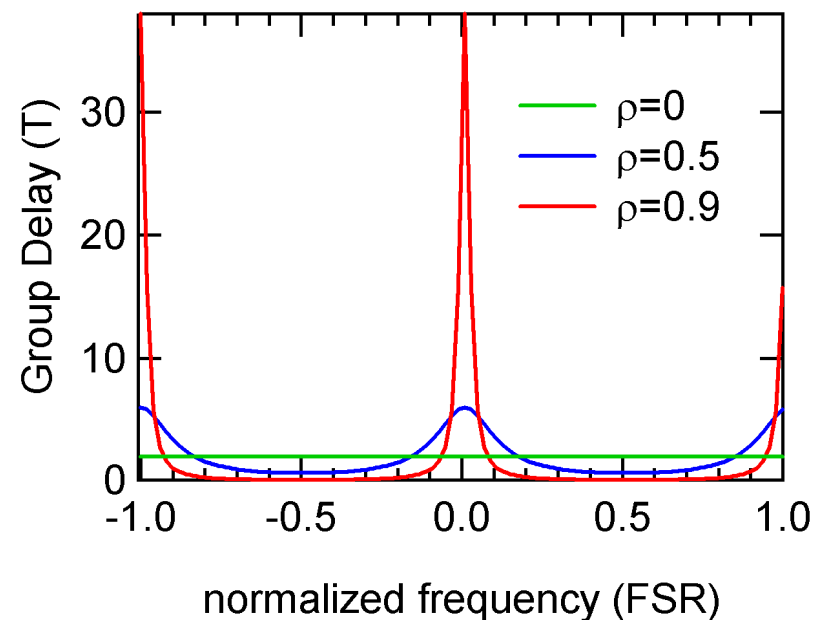
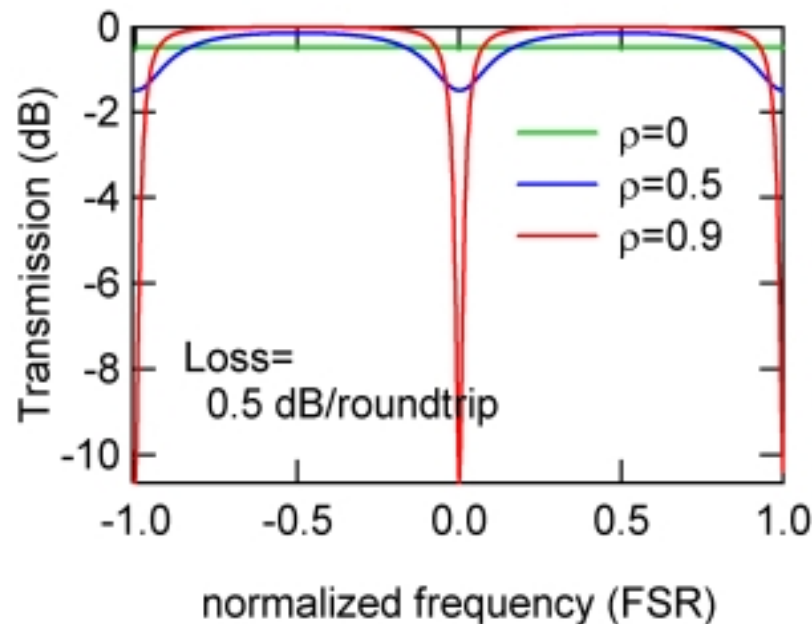
100 GHz Channel Spacing



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All-Pass Filter - Effect of Finite Loss



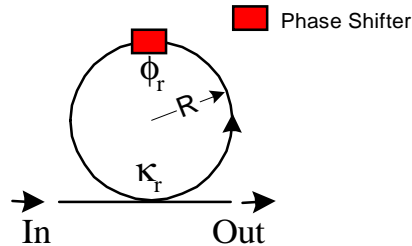
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Broadband All-Pass Filters

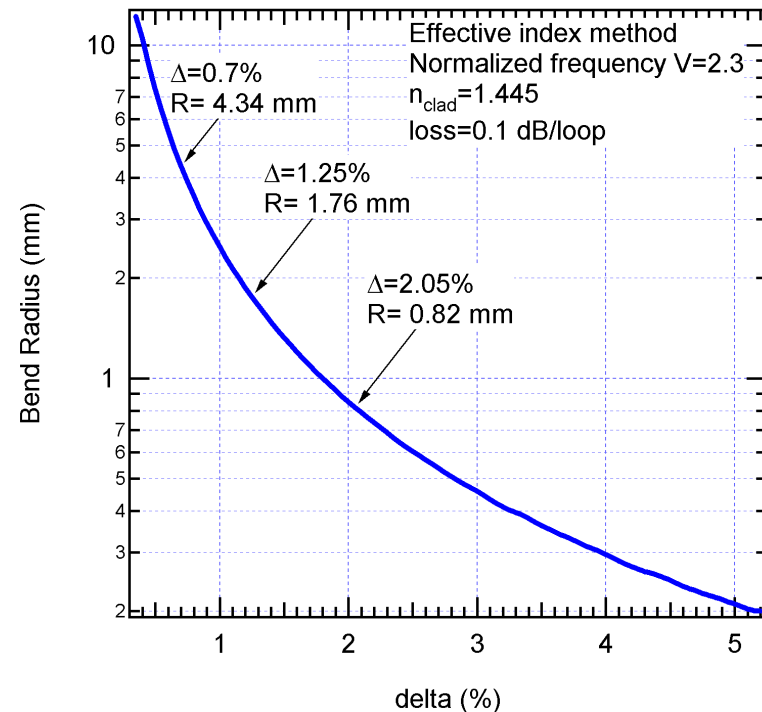
Basic Design



$$FSR \uparrow \Rightarrow R \downarrow \Rightarrow \Delta \uparrow$$



Achieving required coupling κ
practically not feasible

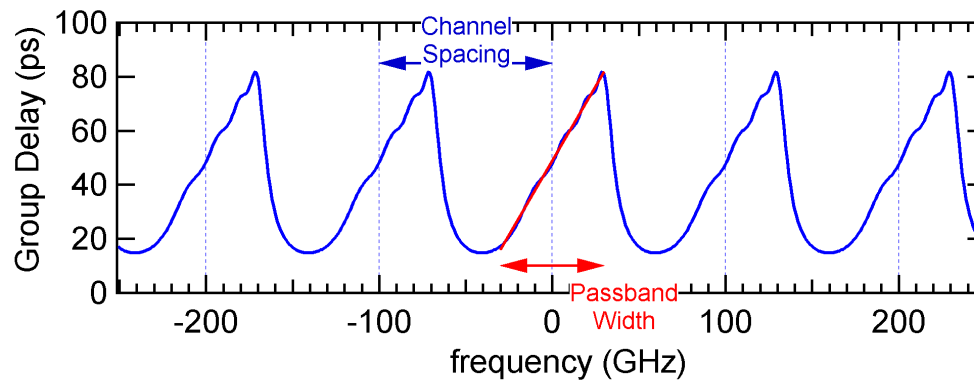


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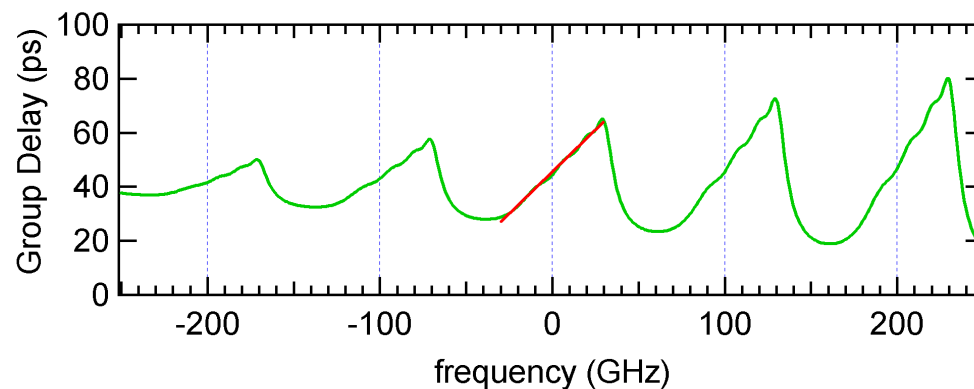
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Multi-channel Dispersion Compensation



Constant
dispersion
compensation



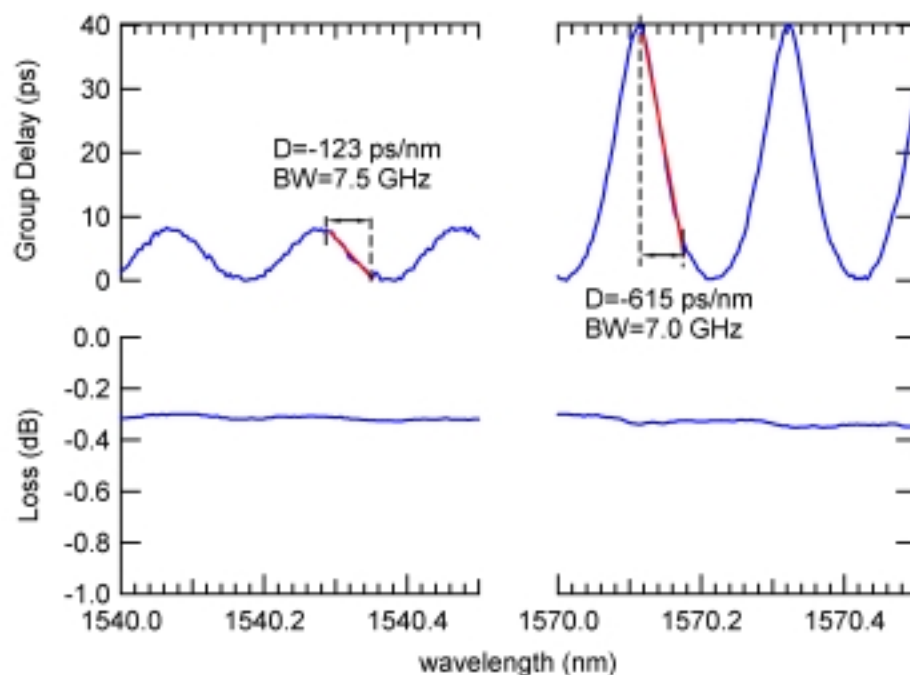
Dispersion
slope
compensation

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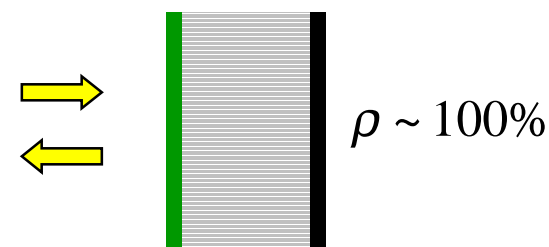
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Thin-film All-Pass Filter

Single-stage Silica substrate (25 GHz FSR)



Package loss 0.3 dB



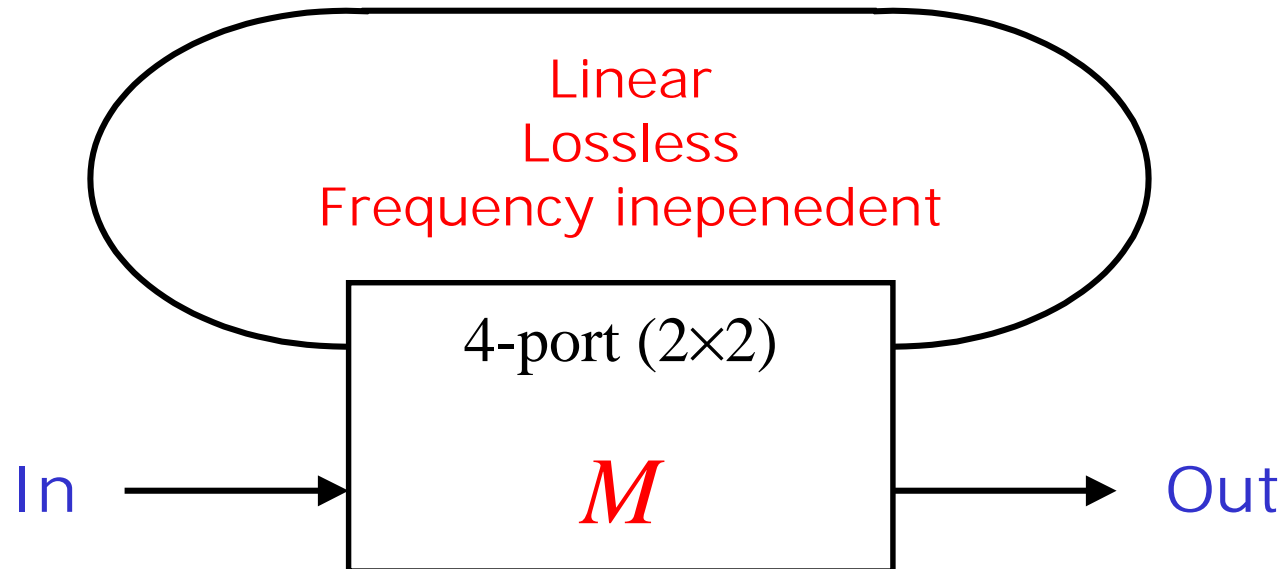
Gires-Tournois
Interferometer (GTI)

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General Construction of an All-Pass Filter



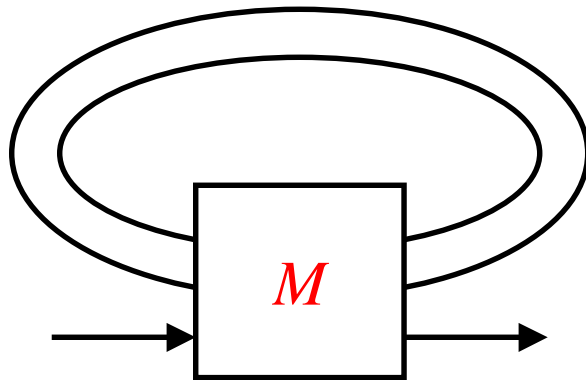
This is an all-pass filter if:

1. $\det(M) = 1$
2. $M_{22} = M_{11}^*$

FSR determined by
feedback path delay



More General All-Pass Structures



$$\det(M) = 1$$

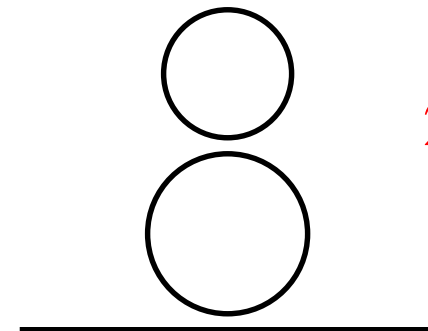
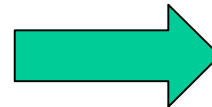
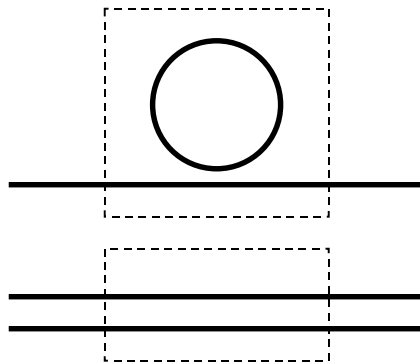
$$M_{11}^* = M_{22}M_{33} - M_{23}M_{32}$$

$$M_{22}^* = M_{11}M_{33} - M_{13}M_{31}$$

$$M_{33}^* = M_{22}M_{11} - M_{21}M_{12}$$

*Single stage
APF*

Coupler



*2-stage
APF*

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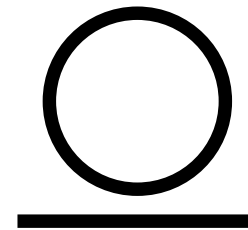
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Simple Case



Directional coupler



*Single stage
all-pass filter*

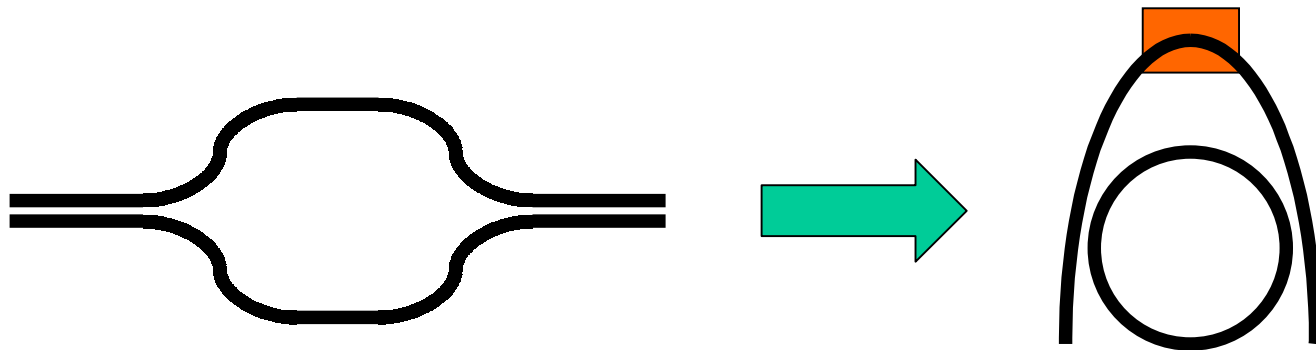
Scaling problem:



Larger FSR \Rightarrow Smaller rings \Rightarrow Larger
bend loss \Rightarrow Larger Δ material \Rightarrow Coupler
gap too small



MZI-based APF

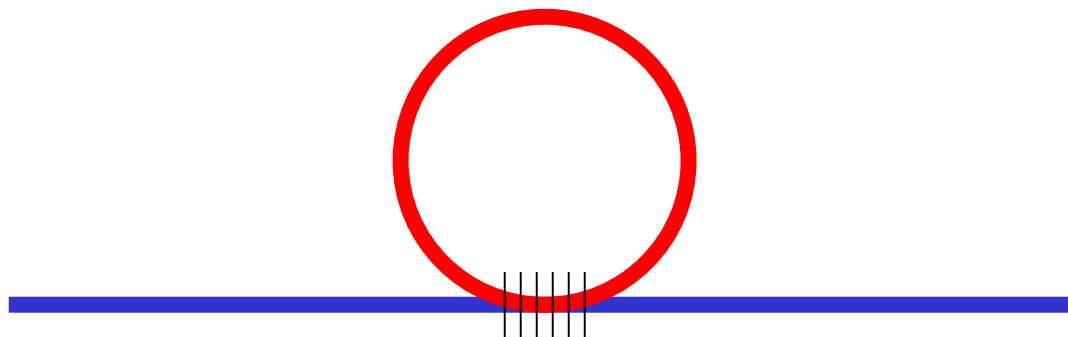


This design is no longer sensitive to the couplers

Equivalent to simple case, but with **tunable coupling**



Another solution



Vertical grating-assisted coupling

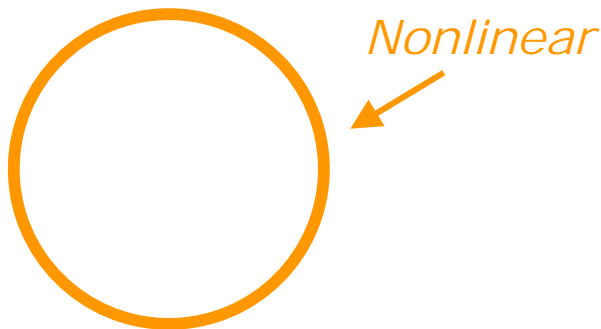


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Nonlinear all-pass filters



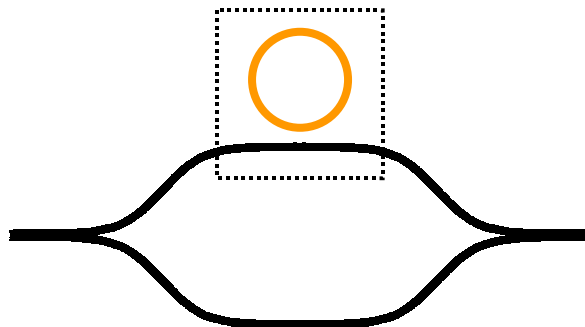
$$\Phi_{eff} \sim \left(\frac{2\pi}{\lambda} n_2 IL \right) 4F^2$$

$$F \sim \frac{\tau_{max}}{T}$$

However, large F implies
small bandwidth



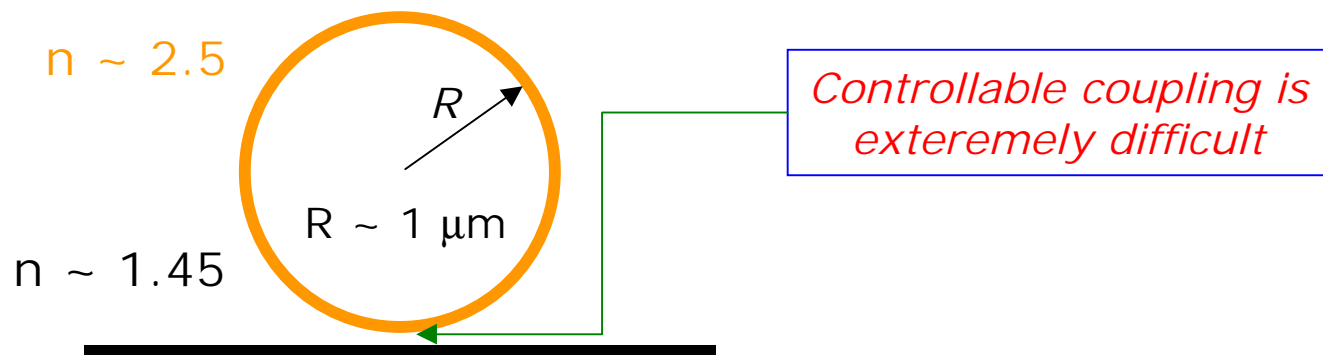
For ~ 1 ps timescales
requires very small rings
or disks ($\sim 1 \mu\text{m}$)



(Heebner and Boyd, *Opt. Lett.*, 1999)

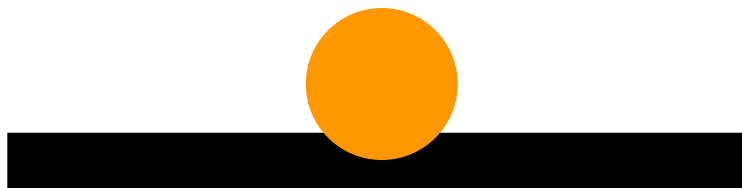


Practical considerations



Vertical coupling

$R \sim 1 \mu\text{m}$
 $F \sim 30$
 Cavity losses?





Summary

- *Ring resonators can be used as tunable optical phase equalizers*
- *Large bandwidth devices require many small rings*
- *Ring loss needs to be minimized*
- *Nonlinear micro rings may be used for fast all-optical switching*